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Characteristics of sunflower seed drying and microwave energy consumption

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A b s t r a c t. The effect of the microwave-convective drying technique on the moisture ratio, drying rate, drying time, effective moisture diffusivity, microwave specific energy consumption, and energy efficiency of sunflower seeds were investigated. Drying took place in the falling rate period. Increasing the microwave power caused a significant decrease in the drying time. The drying data were fitted to four thin-layer drying models. The performance of these models was compared using the coefficient of determination, reduced chi-square and root mean square error between the observed and predicted moisture ratios. The results showed that the Page model was found to satisfactorily describe the microwave-convective drying curves of sunflower seeds. The effective moisture diffusivity values were estimated from Fick diffusion model and varied from 1.73 10^{-7} to 4.76 $10^{-7} m^2 s^{-1}$. Increasing the microwave power resulted in a considerable increase in drying efficiency and a significant decrease in microwave specific energy consumption. The highest energy efficiency and the lowest microwave specific energy consumption were obtained at the microwave power of 300 W.

K e y w o r d s: drying, modelling, sunflower seed, microwave energy consumption

INTRODUCTION

Sunflower is one of the world major oil seed crops. Harvesting sunflowers with high moisture content normally results in higher yields, less bird damage and less head dropping and shattering. As the fall season progresses, drying is probably mandatory so harvesting can be completed. The drying process is an important mass and heat transfer mechanism in oil seeds. Since oil seeds are heat-sensitive due to their composition, their quality may suffer if they are exposed to excessive heat.

Sunflower seeds can be safely stored at 10% moisture or less, but during warmer months the storage moisture should be at 8% or less (Bax *et al*., 2004; Myers, 2002). Sunflower seeds are dried usually by the use of forced air through the batch of seeds. The common hot air drying of foods brings the disadvantages of low energy efficiency and lengthy drying time especially during the falling rate period. Also, the primary problem is that small fibres rub off the sunflower hulls and float in the air.

Improving drying processes by reducing energy consumption and providing a high quality with a minimal increase in the economic input have become the goal of modern drying over the past two decades, there has been an increasing interest in microwave drying to reduce drying time and increase removal of water from agricultural products. Microwave drying has several advantages such as a higher drying rate, shorter drying time, decreased energy consumption, and a better quality of the dried products (Vadivambal and Jayas, 2007).

Most of the previous studies on drying of sunflower seeds have focused on convective hot-air drying, and the effects of air temperature, relative humidity and initial moisture content on drying kinetics, oil quality and germination. There is no available report regarding the effectiveness of intermittent microwave drying of sunflower seeds compared to conventional drying techniques.

Therefore, the aim of this study was to:

- investigate the characteristics of microwave-convective drying of sunflower seeds,
- develop suitable mathematical models to describe the drying characteristics,
- discuss the influence of microwave power on energy efficiency and specific energy consumption,
- establish the optimum drying condition for sunflower seeds based on drying kinetics and in respect to energy consumption.

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MATERIALS AND METHODS

Sunflower seeds harvested from the experimental farm in Ilam, Iran, were used in the study. Samples were stored in a refrigerator at 5°C prior to the drying experiments. Five different samples, each weighing 50 g, were kept in a drying oven at 105±1°C for 24 h (Gupta and Das, 2000) after which the moisture content of sunflower seeds fell down to 31.10±0.75% on wet basis (w.b.).

The microwave-convective dryer consists of microwave oven (M945, Samsung Electronics Ins) with a maximum output of 1000 W at 2450 MHz, a variable speed fan and a digital balance (GF-600, A and D, Japan) with an accuracy of ±0.01 g. Air velocity was kept at a constant value of 1 m s^{-1}. A sample tray in the microwave oven chamber was suspended on the balance with a nylon wire through a ventilation hole in the centre of the chamber ceiling. The area on which microwave-convective drying was carried out was 350× 350×240 mm in size. The samples were dried in the microwave dryer at four output powers of 200, 300, 400, and 500 W. The thickness of the samples was about 2.25±0.1 cm with initial load of 50±1 g. The temperature and relative humidity of the ambient air room were 22±1°C and 5%, respectively. The moisture loss of the sample was recorded by means of a weighing system at 30 s intervals during drying. Each drying process was applied until the initial moisture ratio (*MR*) was reduced to 1.5% dry basis (d.b.).

In most studies carried out on drying, diffusion is generally accepted to be the main mechanism during the transport of moisture to the surface to be evaporated. The effective moisture diffusivity (D_{eff}) can be determined from the slope of the normalized plot of the unaccomplished moisture ratio, ln(*MR*) vs time, using the following equation:

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}}{4L^2}\right)t, \qquad (1)$$

where: *MR* is the moisture ratio (%), *t* is the drying time (s), D_{eff} is the effective moisture diffusivity ($m^2 s^{-1}$), and L is the half-thickness of the thin-layer sample (m).

For mathematical modelling, the thin-layer drying equations in Table 1 were tested to select the best model for describing the drying curve of sunflower seeds. The coefficient of determination (R^2), reduced chi-square (χ^2) and root mean square error (RMSE) were used to determine the quality of the fit. The higher the value of R^2, and the lower the values of χ^2 and RMSE, the better goodness of fit is observed (Aghbashlo *et al*., 2009; Liu *et al*., 2009).

In the microwave-convective dryer, the consumed energy is the sum of energy consumed by the microwave oven and the ventilator fan used for moving the air. The specific energy consumption by ventilator fan during drying was just 0.012-0.031% of the specific energy consumption, and could be neglected without any loss in accuracy.

Table 1. Mathematical models given by various authors for drying curves

Model name	Model	References
Lewis	$MR = \exp(-kt)$	El-Beltagy *et al*. (2007)
Henderson and Pabis	$MR = a\exp(-kt)$	Liu *et al*. (2009), Aghbashlo *et al*. (2009)
Page	$MR = \exp(-kt^n)$	Vega-Gálvez *et al*. (2010)
Wang and Singh	$MR = 1 + bt + at^2$	Arumuganathan *et al*. (2009)

k is the drying constant (min^{-1}), and *a, b, n* are equation constants (dimensionless).

The energy consumed for drying a kilogram of sunflower seeds is calculated using Eq. (2) (Kassem *et al*., 2011; Motevali e*t al*., 2011):

$$Q = \frac{Pt}{m_w}, \qquad (2)$$

where: *Q* is the microwave specific energy consumption (J kg^{-1} water), *P* is the microwave power (W), and m_w is the total mass of evaporated water (kg).

The microwave energy efficiency was calculated as the ratio of heat energy utilised for evaporating water from the sample to the heat supplied by the microwave oven (Soysal *et al*., 2006):

$$\eta = \frac{m_{wt}\,\lambda_w}{Pt}, \qquad (3)$$

where: η is the microwave energy efficiency (%), m_{wt} is the mass of evaporated water at any time (kg), and λ_w is the latent heat of vaporization of water (J kg^{-1}). The average values of microwave energy efficiency were calculated as the averaged energy consumption for water evaporation divided by the supplied microwave energy in the total power-on time (Soysal *et al*., 2006).

RESULTS AND DISCUSSION

The moisture content of the sunflower seeds at each power input was reduced from 45.2 to 1.5% dry basis. It was found that the moisture content was affected by the microwave power input and the drying time of the leaves was significantly reduced from 12.5 to 3.5 min as the power input increased (Fig. 1). The results indicate that mass transfer within the sample was more rapid during higher microwave power heating because more heat was generated within the sample, resulting and substantial difference in the vapour pressure between the centre and the surface of the product due to the characteristic microwave volumetric heating.

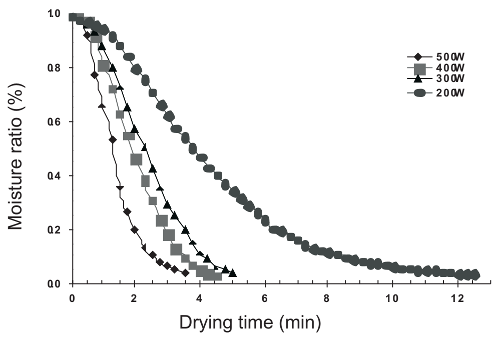

Fig. 1. Moisture ratio versus drying time of sunflower seed at different microwave powers.

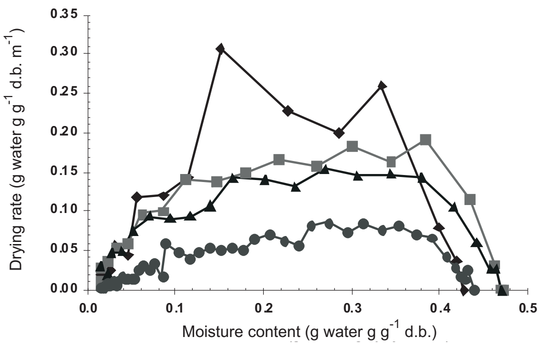

Fig. 2. The relations between the drying rate and moisture content of sunflower seeds at different microwave powers. Explanations as in Fig. 1.

The drying rates were determined from the amount of water removed per unit time and per unit dry basis. It was observed that the drying rates were higher at the beginning of the drying operation, when the product moisture contents were higher (Fig. 2). The moisture content of the material was very high during the initial phase of the drying, which resulted in higher absorption of microwave power and higher drying rates due to the higher moisture diffusion. As the drying progressed, the loss of moisture in the product caused a decrease in the absorption of microwave power and resulted in a fall in the drying rate. The drying of sunflower seeds did not display a constant rate period, but it occurred in the falling-rate period. This result shows that diffusion is the dominant physical mechanism governing moisture movement in microwave-convective drying of sunflower seeds.

Non-linear regression analysis was used to estimate the parameters of those models. The statistical results from models are summarized in Table 2. The best model describing the thin-layer drying characteristics of sunflower seeds was chosen as the one with the highest R^2 value and the lowest χ^2 and RMSE values. The statistical parameter estimations showed that R^2, χ^2, and RMSE values ranged

Table 2. Results of statistical analysis on the modeling of moisture content and drying time for the microwave-convective dried sunflower seed

Model name	*P* (W)	Model constants	R^2	χ^2	RMSE
Lewis	500	k=0.8770	0.945	0.02099	0.13997
	400	k=0.6438	0.879	0.03012	0.16892
	300	k=0.5248	0.859	0.02903	0.16626
	200	k=0.2658	0.969	0.01088	0.10327
Henderson and Pabis	500	a=1.4947, k=1.0433	0.979	0.02314	0.14697
	400	a=1.7699, k=0.8290	0.944	0.05055	0.21884
	300	a=1.7304, k=0.6853	0.929	0.04676	0.21103
	200	a=1.3918, k=0.3051	0.991	0.00735	0.08489
Page	500	k=0.428, n=1.901	0.996	0.00054	0.02254
	400	k=0.193, n=1.991	0.999	0.00011	0.01037
	300	k=0.136, n=1.998	0.999	0.00004	0.00630
	200	k=0.080, n=1.598	0.997	0.00027	0.01627
Wang and Singh	500	a=0.0521, b= -0.4724	0.961	0.00534	0.07062
	400	a=0.0108, b= -0.2832	0.967	0.00436	0.06427
	300	a= 0.0021, b= -0.2213	0.972	0.00349	0.05761
	200	a=0.0065, b= -0.1594	0.980	0.00227	0.04714

from 0.859 to 0.999, 0.00004 to 0.05055, and 0.00630 to 0.21884, respectively. Of all the models tested, the Page model gave the highest value of R^2 and the lowest values of χ^2 and RMSE. Thus, it was selected to represent characteristics of thin-layer drying of sunflower seeds.

The proposed model provided conformity between the experimental moisture ratio (MR_{exp}) and predicted moisture ratio (MR_{pred}) (Fig. 3). There was a very good agreement between the MR_{exp} and MR_{pred}, which closely banded around a 45° straight line. The Page model has also been suggested by others to describe the thin-layer drying of rapeseed (Kumar *et al*., 2009), microwave hot air drying of Thompson seedless grapes (Kassem *et al*., 2011), and solar drying of *Cuminum cyminum* (Zomorodian and Moradi, 2010).

It was determined that the value of k increased with the increase in the microwave power. This data indicates that, with the increase in the microwave power, the drying curve becomes steeper, indicating faster drying of the product. A similar trend was observed by Ozkan *et al*. (2007) for spinach as well as Sharma and Prasad (2001a,b) for garlic cloves. The regression equations of constants of the Page model against the microwave power level are represented as follows:

$$k = 0.0263 \exp(0.0054P) \quad R^2 = 0.975, \tag{4}$$

$$n = -10^{-5} P^2 + 9.5\ 10^{-3} P + 0.2088 \quad R^2 = 0.951. \tag{5}$$

The variation in ln(MR) and drying time (t) for different microwave powers have been plotted in Fig. 4 to obtain the slope (Eq. (1)) which can give the effective moisture diffusivity. The D_{eff} values of dried samples at microwave power level of 200-500 W were varied in the range of 1.73 10^{-7} to 4.76 10^{-7} m^2s^{-1}(Table 3). It can be seen that D_{eff} values increased greatly with the increasing microwave power level. The higher power level caused an increase in effective moisture diffusivity because of higher mass transfer. The values of D_{eff} obtained from this study lie within the general range 10^{-12} to 10^{-8} m^2s^{-1} for drying of food materials (Arumuganathan *et al*., 2009). The values of D_{eff} are comparable with the reported values of 1.0465 10^{-8} to 9.1537 10^{-8} m^2s^{-1} mentioned for apple pomace microwave drying (Wang *et al*., 2007), 1.14 10^{-6} to 6.09 10^{-6} m^2s^{-1} for tomato pomace microwave drying at 160-800 W (Al-Harahsheh *et al*., 2009), and 0.55 10^{-7} to 3.5 10^{-7} m^2s^{-1} for *Gundelia tournefortii* microwave drying at 90-800 W (Evin, 2011). The relationship between effective moisture diffusivity and microwave power can be represented as:

$$D_{eff} = 8.7\ 10^{-10}\ P^{1.0019} \quad R^2 = 0.917 \tag{6}$$

The variation of microwave energy efficiency with moisture content is shown in Fig 5. The microwave energy efficiency was very high during the initial phase of the drying, which resulted in higher absorption of microwave power and higher drying rates due to the higher moisture diffusion. Following moisture reduction, the energy absorbed by the product decreased and the reflected power increased (Araszkiewicz *et al*., 2004; Mousa and Farid, 2002; Soysal *et al*., 2006). For this reason, it was observed that as the microwave power increased the energy losses increased, in other words, the values of microwave energy efficiency decreased. Similar trends were also observed by Soysal *et al*. (2006) for microwave drying of parsley. The best result with regard to microwave energy efficiency was obtained from 300 W microwave power among all the microwave power levels.

The average microwave energy efficiency and energy needed for drying 1 kg of the samples can be seen from Fig. 6. As it is understood from this figure, the minimum heat energy (5.81 MJ kg^{-1}) is needed for drying of 1 kg sunflower seeds at microwave power of 300 W. The values of the average efficiency of microwave energy varied between 22.16

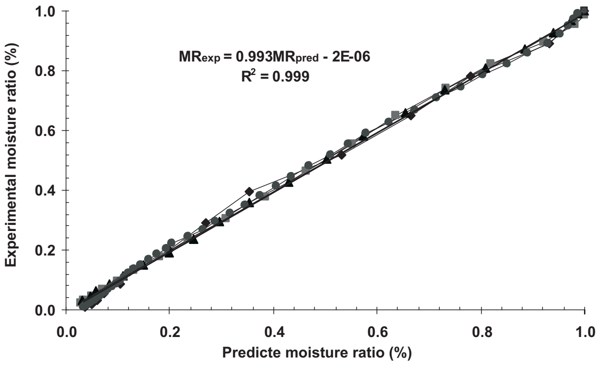

Fig. 3. Experimental versus predicted moisture ratio values for sunflower seed drying. Explanations as in Fig. 1.

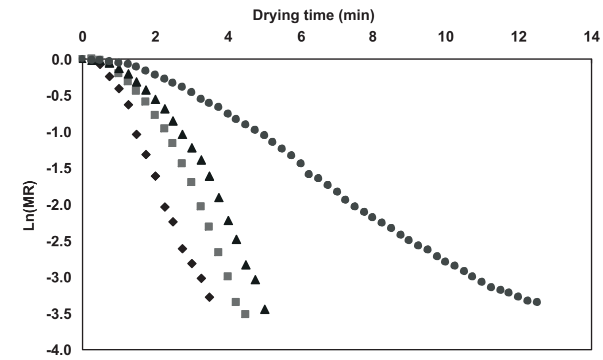

Fig. 4. Plot of ln(MR) versus drying time used for determination of effective moisture diffusivity. Explanations as in Fig. 1.

T a b l e 3. Effective diffusion coefficient of sunflower seed at different microwave power

P (W)	$D_{eff} 10^7$
500	4.76
400	3.01
300	2.94
200	1.73

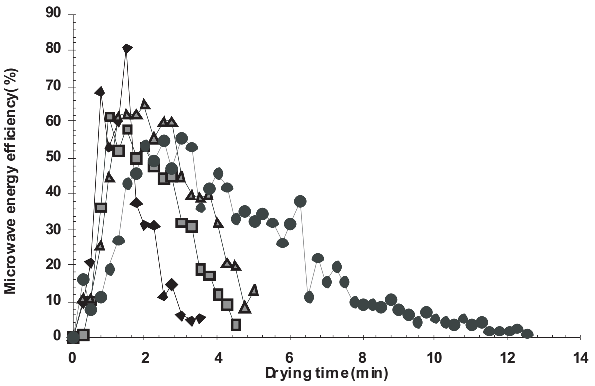

Fig. 5. Microwave energy efficiency versus drying time for sunflower seed drying. Explanations as in Fig. 1.

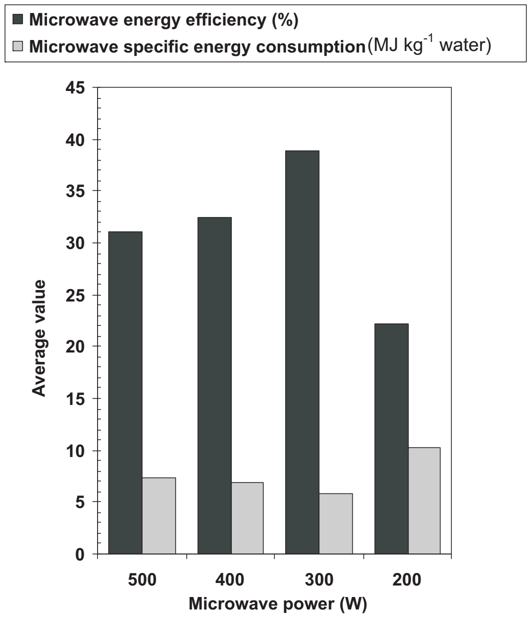

Fig. 6. Average of microwave energy efficiency and specific energy consumption at different microwave powers.

and 31.03%. Besides, the microwave specific energy consumption is decreasing with increasing drying microwave power. One reason might be that the drying time is longer under lower power and result in the increase of microwave energy consumption. Sharma and Prasad (2001a,b) concluded that microwave-convective drying provided 65.5-70% energy saving as compared to convective drying processes. This reduction in microwave energy consumption was due to the volumetric heating effect caused by microwaves, which reduced the drying time considerably.

CONCLUSIONS

1. The entire drying process occurred in the falling rate period and no constant rate period was observed.

2. The drying rate increased with the increase in the drying microwave power, hence reducing the drying time.

3. The effective moisture diffusivity computed from Fick second law and the values varied between 1.73 10^{-7} to 4.76 10^{-7} m^2 s^{-1}, with higher values for the higher microwave power.

4. The Page model was the best mathematical model for describing the drying kinetics of sunflower seeds.

5. The optimum value of microwave specific energy consumption was obtained at 300 W microwave power level.

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